A METHODOLOGY FOR ASSESSING AND RANKING BALLISTIC MISSILE DEFENSE TECHNOLOGIES USING A SYSTEM PERFORMANCE INDEX

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Abstract[*]

The question of where to best invest limited research and development funds is a major concern. In missile defense the problem is exacerbated by the diversity of technologies that may be employed. Frequently, subjective methods such as the Delphi method and various weighting schemes are employed to rank choices. This paper introduces an objective methodology that avoids the problems encountered in subjective weighting schemes. It utilizes a System Performance Index (SPI) based on the physics of the problem as a unifying measure for assessing and ranking diverse technologies. The SPI is coupled with five other measures --- resources, cost, return on investment, technology readiness level, and time of insertion --- to completely characterize the technology with respect to a baseline.   The SPI is calculated as the summation of the product of the Probability of Zero Leakage and the Value of the target area over the entire defended region. The methodology utilizes an abstract system model that embodies the physics of the problem and operates with Critical Performance Parameters that can be derived for the technologies using well-established analytical models and processes.   Available tools for implementing the methodology and shortcomings are discussed, and the methodology is demonstrated through and example.

Introduction

When you can measure what you are speaking about and express it in numbers,
you know something about it.

Lord Kelvin

The question of where to "best" invest limited research and development dollars is always a major concern to system managers, engineers, and scientists. Ballistic missile defense (BMD) technologies are broad and diverse; thus, making comparison of choices complex and difficult. Frequently, subjective methods such as the Delphi method and various weighting schemes are employed to rank choices. The Delphi method attempts to draw upon the expertise of experts in the field to make "smart" choices. While the Delphi method is useful for quickly screening a large number of choices, it is often difficult to find individuals with expertise across the many technologies that may be employed throughout a BMD system. Consequently, choices of investment strategies sometimes look more like a beauty contest than objective decision-making. Furthermore, the process may become highly politicized. Weighting schemes suffer from similar problems. In these cases there is the problem of picking the weights. Usually, this is a subjective process with little to guide the selection except the experience and "feel" of the selector. This gives rise to the adage, "He who chooses the weights determines the outcome." Unless there is a quantitative method for picking the weights, the process may deteriorate into a political process. Sometimes, complex simulations are constructed to compute effectiveness. This approach, while yielding good results, may be costly and time consuming. Furthermore, some objective method of making comparisons is still required.

Fundamentally, there are three questions the program manager or system engineer wants answered with respect to new technologies. These are:

- o   How will it help solve my problem?
- o   What will it cost?
- o   When will it be available?

The first question can be viewed as a system performance issue, although some might argue that it includes affordability and availability as well. We argue that these are resource issues and are best considered as part of the cost question, which includes research and development, acquisition, and operation and support costs to achieve a specified level of

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Abstract

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system performance. Several cost models [1,2] are available to answer the second question once the system element resources have been quantified. Systems such as NMD, THAAD, PATRIOT, and MEADS also have lifecycle cost (LCC) models that may be used in specific cases. The third question is a schedule question driven primarily by the technology readiness and funding constraints.

In this paper an objective methodology is outlined that supports decisions, which are driven by the physics of the problem rather than the politics of the problem. During the mid-to-late 1980s, the USASMDC investigated and developed methods and performance measures for designing, evaluating, and controlling large-scale Strategic Defense Initiative (SDI) systems. This methodology work [3,4,5] demonstrated the effectiveness of system performance indices as a methodology for optimizing performance of complex systems (and systems of systems) over a range of complex decisions and provides the foundation for the methodology presented in this paper. Results were validated with data from high fidelity testbeds for Low Altitude Defense Systems and SDI Battle Management/Command, Control, and Communications systems. In this paper we build on this foundation and extend the methodology to assess and rank technology choices.

The System Performance Index

Previous work [3,4,5] has demonstrated the use of a System Performance Index in optimizing BMD systems. This work chose the formulation,

$$SPI = \sum P_{si} * V_i \qquad (1)$$

where, P_{si} is the probability of survival of the ith defended asset and V_i is the value assigned to the ith defended asset. Summing over all i assets yields the expected surviving value. Thus, to find the "best" choice only requires that we make choices that maximize the System Performance Index, SPI. For complex systems, computation of the SPI requires an abstract model or simulation that computes the probability of survival based on fundamental physical principals. This process requires algorithms that capture the essential physics constraining or driving the performance of the system at a level of fidelity that will enable an accurate distinction to be made between system alternatives.

At first glance this may seem to be a daunting a task, however, we only have to find the P_{si} for each defended asset impacted by our choices. If we are considering new technologies for incorporation in the BMD system, this is a relatively small set. Thus, we are able to compute SPI for all choices and use the results to rank order the choices, i.e., rank the technologies.

When equation (1) was formulated, the threat was counted in the thousands and many of the defended assets were hard targets. Today, the threat is vastly different. The threat is counted in tens and most of the targets are soft, i.e., cities, population centers, etc. Consequently, today there is emphasis on the probability of zero leakage P_{ZL} as a measure of performance. Thus, the SPI can be reformulated to

$$SPI = \sum P_{ZLi} * Vi. \qquad (2)$$

While the equation (2) formulation is not precisely equivalent to equation (1), it is approximately equivalent assuming soft targets and relatively small, defended areas. With equation (2), we now have a formulation that can be used to optimize among available choices. In comparing technologies it may be convenient to normalize the SPI as follows,

$$SPI = \sum P_{ZLi} * V_i / \sum V_i \qquad (3)$$

to provide a SPI that varies between 0 and 1.

Technology Assessment and Ranking Methodology

The SPI provides an objective quantitative means of assessing and comparing the impact of diverse technologies on system performance. We will discuss an overall methodology for computing the SPI, quantifying cost, assessing readiness for insertion in the system, and using the results to rank the technologies.
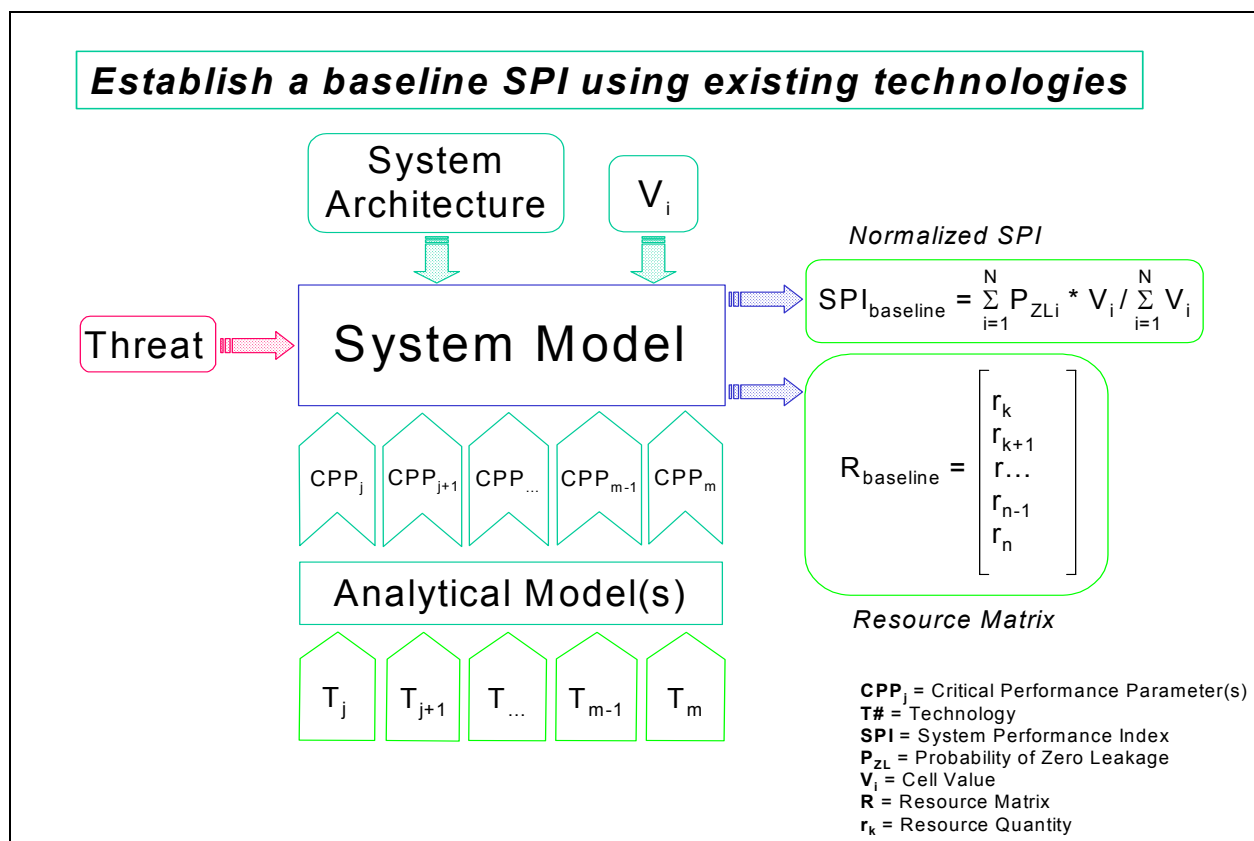
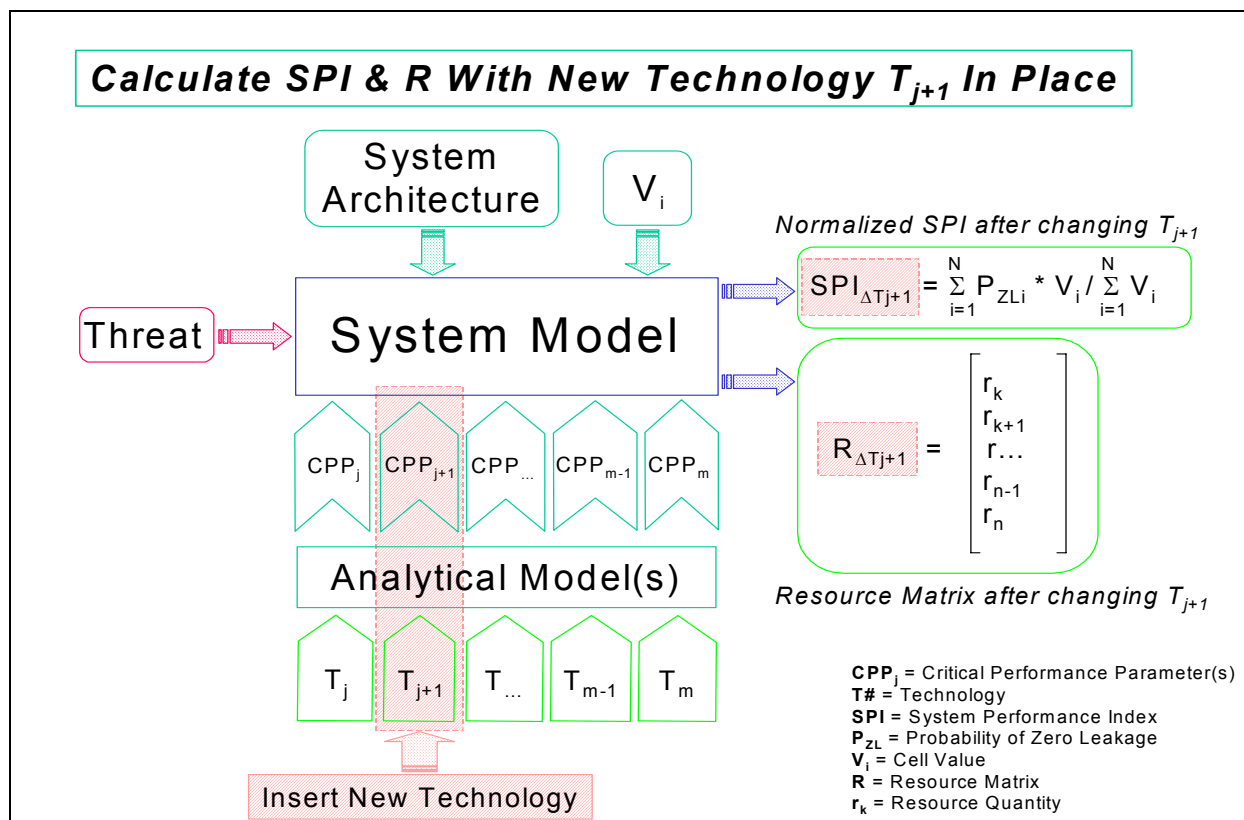**Figure 1. Process for Establishing the Baselines for SPI and Resources**

Establishing a Baseline

The methodology starts with the establishment of a baseline system performance index, $SPI_{baseline}$, and associated resources, $R_{baseline}$, for the baseline technologies used in the system. This process is illustrated in Figure 1. The process uses a System Model that embodies the System Architecture and responds to a Threat model to compute the SPI and the associated R. Threat evolution is an important consideration in the final technology ranking process. The SPI will vary in response to changes in threat over time. A full analysis will entail determination of the SPI for different "threat epochs" corresponding to periods of time when a particular threat suite is projected to emerge and/or predominate. The key to success with this process is a System Model that represents the system at the right level of abstraction. It must provide outputs that can be used to compute the P_{ZL} associated with each defended asset or area. The model must embody the basic physics of the problem and operate with Critical Performance Parameters (CPP) that can

be derived for the technologies using well-established analytical models and processes. A typical analytical model might use the radar range equation, sensor sensitivity, etc. to generate CPPs. Example CPPs include detection range, discrimination range, interceptor flyout fans, etc. that can be derived from the characteristics of the technologies, T.

Calculate SPI and R with New Technology

The next step is to calculate the SPI and associated resources, R, with the new technology inserted. The new technology, T, will impact one or more Critical Performance Parameters (CPP), which will in turn be reflected in the response of the System Model to the Threat. It does not matter if a new technology generates an SPI value by influencing several CPPs or by influencing a single CCP. In either case the influence of the technology on the SPI will be properly calculated. It is important to distinguish between this approach and weighting schemes that are not driven by impact on

Calculate SPI & R With New Technology T_{j+1} In Place

System Architecture

V_i

Threat

System Model

Normalized SPI after changing T_{j+1}

$$SPI_{\Delta Tj+1} = \sum_{i=1}^{N} P_{ZLi} * V_i / \sum_{i=1}^{N} V_i$$

CPP_j CPP_{j+1} $CPP_{...}$ CPP_{m-1} CPP_m

$$R_{\Delta Tj+1} = \begin{bmatrix} r_k \\ r_{k+1} \\ r... \\ r_{n-1} \\ r_n \end{bmatrix}$$

Analytical Model(s)

Resource Matrix after changing T_{j+1}

T_j T_{j+1} $T_{...}$ T_{m-1} T_m

CPP_j = Critical Performance Parameter(s)
T# = Technology
SPI = System Performance Index
P_{ZL} = Probability of Zero Leakage
V_i = Cell Value
R = Resource Matrix
r_k = Resource Quantity

Insert New Technology

Figure 2. Process for Calculating the SPI & R with New Technology

system performance. Weighting schemes that rely on a preponderance of data or opinion generally will not properly capture the cumulative effect of a technology across multiple CPPs, and can be a major source of error in ranking.
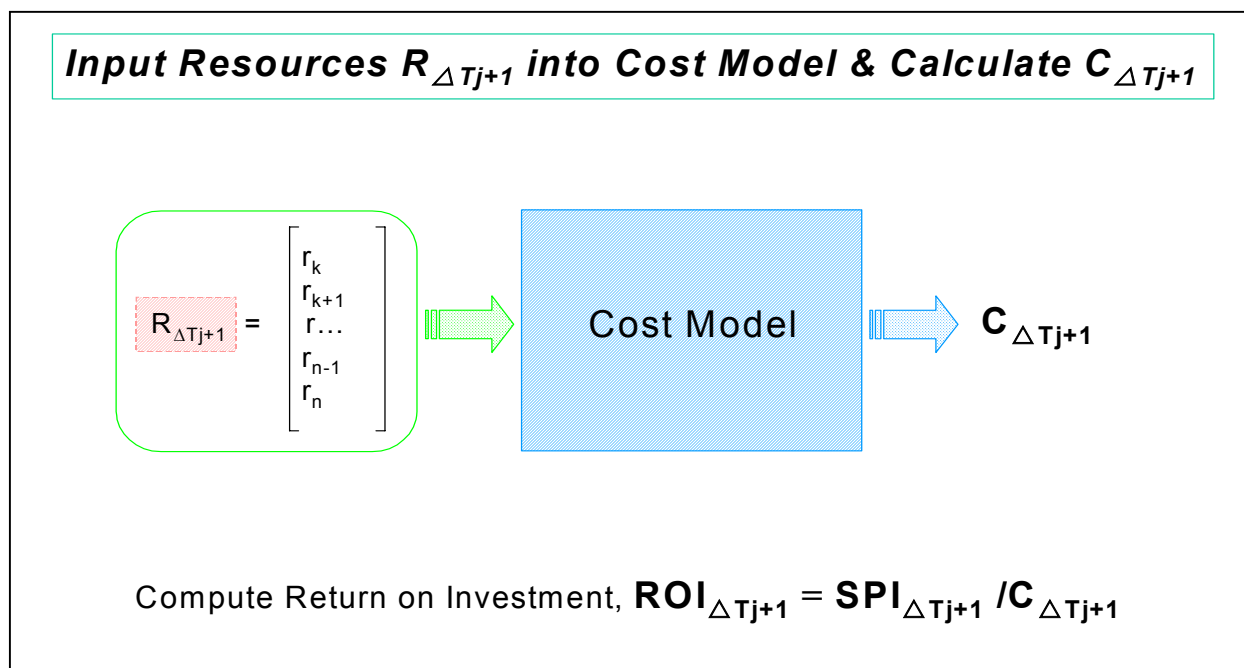
The overall process for calculating SPI and R is illustrated in Figure 2. The results are a new SPI and resource matrix, R, that can be compared to the established baseline. We now have a quantitative measure of the improvement offered by the new technology and a basis for estimating the associated cost.

Calculate Cost and Return on Investment
The next step in the methodology is to estimate the cost associated with the baseline and the new technology. The approach is illustrated in Figure 3. The resource matrix, R, from the System Model is input to a Cost Model to obtain an estimate of the cost associated with the level of system performance denoted by the SPI for each technological innovation. It also may be useful to normalize the cost to the baseline cost. The cost model must produce an estimate of the

total lifecycle cost to include Research, Development, Test, and Evaluation (RDT&E); System Acquisition; and Operation and Support (O&S).   This model could be the existing lifecycle cost (LCC) model for the system, or for that matter several different system LCC models or element cost models could be used to support the cost estimation requirement.   Note, the previous Large Scale Systems Technology work discussed previously addressed only system resources and did not specifically address detailed cost modeling.   In this respect, the process outlined in this paragraph represents an extension of that methodology.

A simple calculation of Return On Investment (ROI), based on the SPI and Cost, provides another measure that is extremely useful in the final ranking process because it allows us to consider cost reduction technologies and performance enhancing technologies in the same frame of reference. The ROI is computed by dividing the SPI by the Cost, C. This measure indicates which technologies yield the most performance for an investment dollar. Although ROI cannot be used alone, it is very

$$\boxed{\textit{Input Resources } R_{\Delta Tj+1} \textit{ into Cost Model \& Calculate } C_{\Delta Tj+1}}$$

$$R_{\Delta Tj+1} = \begin{bmatrix} r_k \\ r_{k+1} \\ r\ldots \\ r_{n-1} \\ r_n \end{bmatrix} \Rightarrow \boxed{\text{Cost Model}} \Rightarrow C_{\Delta Tj+1}$$

Compute Return on Investment, $\mathbf{ROI}_{\Delta Tj+1} = \mathbf{SPI}_{\Delta Tj+1} / \mathbf{C}_{\Delta Tj+1}$

Figure 3. Process for Calculating Cost and Return on Investment

useful in ranking technologies that are above a specified system performance threshold, and can, therefore, be very useful in deciding where to make investments.

Technology Readiness
The question of when the technology will be available is complex, comparable to predicting the future. Nine levels[6,7] of readiness have been defined by NASA and adapted by the DOD in an attempt to make the process more quantifiable and objective. Although the technology readiness levels (TRLs) are objective, given a standard interpretation of the definitions, they do not answer the question of when the technology will be available for insertion. However, the TRL does provide a useful approach for assessing where a technology is in its developmental lifecycle. It is tempting to view the TRL as sufficient, but it is of limited value in estimating the time epoch within a system lifecycle when the technology will be ready for insertion into the system because we currently have no models to predict when the technology will be ready for insertion given its current TRL. Unfortunately, today the only way to get this information is for the technologist to develop detailed schedules that show when the technology is ready for insertion. Any estimate, of course, is predicated on the skill of the technologist and the level of available funding. Two schedules are of interest – constrained and unconstrained. The first assumes a level of funding to mature the technology that is less than could be fully utilized. The second assumes funding is not an issue and timelines are constrained only by the technologist's capability to mature the technology. We argue that the unconstrained schedule is the most important for technology assessment and ranking, and that it should be used to determine the Time of Insertion (TOI).

Models based upon empirical or historical data have been successfully developed and widely used to estimate schedules for complex systems. Examples include software estimation models such as COCOMO[8] and REVIC[9]. Comparable models are needed to estimate when the technology will be ready for insertion given where it is in the development cycle (i.e., its TRL), the type of technology, and other technology unique factors. Techniques such as those employed in COCOMO and REVIC may offer fruitful avenues for research in this area. Until such models are available, we will be forced to rely on schedules generated by the technologists to establish the TOI.

Ranking the Technologies

The ranking process begins by ranking the technologies in descending order from the highest SPI to the lowest. The minimum acceptable system performance against a threat is used to establish a threshold level of performance and the maximum cost constraint is used to put a ceiling on the cost we are willing to

support insertion to counter projected threats. Graphically this is illustrated in Figure 4. For capability-based deployments TOI simply represents the earliest deployment opportunity and other metrics such as cost may be the overriding factor. Either way the final result can be used to construct a preliminary block upgrade plan corresponding to the time epochs where
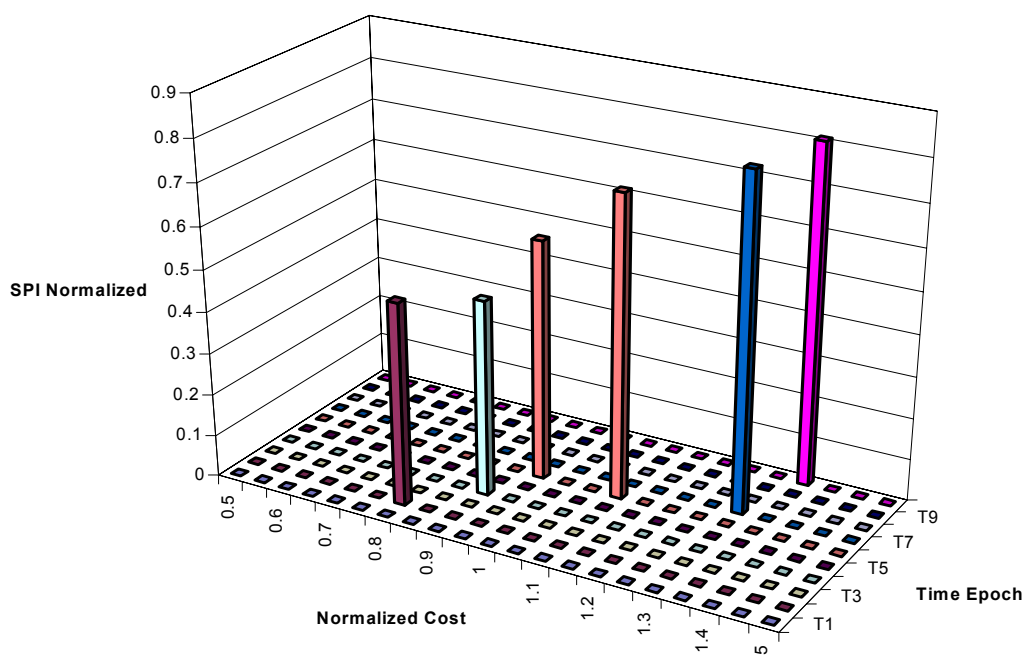

Figure 4. Normalized SPI Plot in Cost-Time Space

incur. Technologies that meet or exceed the threshold level of performance are selected over those that do not, provided they fall within the maximum cost constraint. Technologies that satisfy both of these constraints are reordered in descending order according to their ROI value – highest ROI to lowest.

The next step is to look at the future time epochs where the various technologies are projected to be ready for insertion. Those technologies that counter projected threats with acceptable performance, are within the maximum cost constraint, and fall within or precede time epochs in which the projected threats are viable represent the best choices. Therefore, we rank the technologies in descending order (highest to lowest) according to ROI value (that exceeds the minimum performance threshold and within the maximum cost constraint) that have TOIs, which

capabilities against specific threats are projected to be available.

Implementing the Methodology

The SPI methodology can be implemented with tools that are available today. An overview of the tools and process for calculating SPI and R is shown in Figure 5. One system model that can be used to support the implementation is the Quick Defended Area (QDA) model, which models the system architecture and elements, their performance parameters, and the system response to the threat. QDA has been used extensively in the Ballistic Missile Defense System Architecture Studies (BMDSAS) and to support the assessment of technologies for the Joint Center for Technology Integration (JCTI). As such, it is well proven and has a large repertoire of models for architectural elements and threats suites.
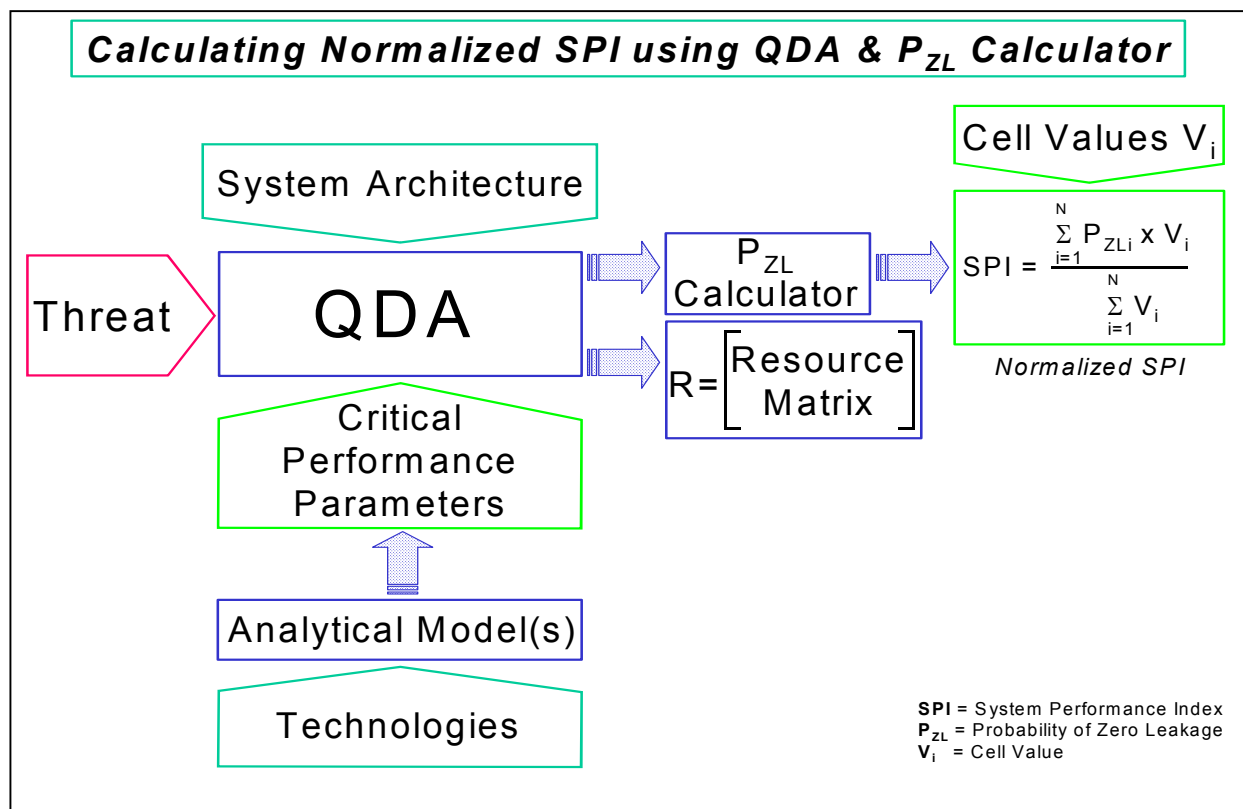
Figure 5. Implementation of Process for Calculating SPI and R

QDA divides the defended area into a grid specified by the user, flies the threats, and computes the engagement opportunities associated with each cell within the grid, based upon the deployment physical constraints and the CPPs for the elements of the system architecture. The outputs are engagement opportunities and resources utilized. CPPs may be calculated using the analytical models from the Analysis Tools developed by Haight[10] or other available models using characteristics of the technologies. Engagement opportunities are input to the P_{ZL} Calculator, which computes the P_{ZL} associated with each cell within the defended area. Cells can take on various values, V_i, corresponding to the system objective. They might take on a uniform value of 1 for all cells if we are only interested in zero leakage; the population within the cell might be used in the case of population defense; or the value of critical military targets within the cells might be used for defense of military assets. The SPI Calculator computes the normalized SPI from the P_{ZLi} and V_i values.

Several cost models are available that could support the requirements of this methodology. The primary requirement is that the model be able to compute the RDT&E, acquisition, and O&S costs using resource requirements and characterizations of the technologies. For mature system concepts the system LCC models could be used. For advanced concepts, other models may offer greater flexibility. In some cases it may be necessary to use several element cost models, such as the GBI Cost Model[2], to obtain the desired results. To ensure consistency across the full range of concepts and technologies, a standard cost model should be adopted to support this requirement. A simple ROI Calculator can be used to support the ranking methodology.

The TRL methodology is well defined and can be directly applied to characterize the maturity of the technology. Today it is a manual process to estimate the time epoch when the technology is ready for insertion; therefore, the TOI must be estimated based on inputs from the technologist. A model to estimate TOI based on the current status of the technology, the technology type

Table 1. Assessment and Ranking of Technology Options

Measure	Value	Baseline	A	B	C	D	E
SPI	Population	490.5	466.4	585.0	617.8	680.9	689.1
SPI	Uniform	4649	4492	5511	6926	7678	7786
$SPI_{Normalized}$	Population	0.65	0.61	0.77	0.81	0.90	0.91
$SPI_{Normalized}$	Uniform	0.48	0.47	0.57	0.72	0.80	0.81
$C_{Normalized}$	$\$B_k/\$B_{BL}$	1.00	0.76	0.56	0.91	1.06	1.10
ROI	SPI/C	0.65	0.80	1.37	0.90	0.84	0.83
TRL	Number	6	5	4	4	4	3
TOI	Time Epoch	T1	T1	T1	T2	T2	T2
Ranking			3	2	1	1	2	3

and other technology unique factors is needed to support the methodology in the future. Techniques using empirical data such as those employed in software estimating tools (e.g., COCOMO or REVIC) may offer fruitful avenues for successful implementation of such a model in the future.

Application of the Methodology
The methodology has been applied to assess and rank five technologies considered for defense of Europe[11]. A summary of the measures for the baseline and each technology concept is provided in Table 1. The SPI is calculated for two Value metrics --- one based on population[12] within the cell and a second that assumes all cells are of uniform value. Note, different defended area values yield different values for SPI metrics. Also we have not included R because it is beyond the scope of this paper.

Ranking by ROI yields B, C, D, E, and A, all with better ROI than the Baseline. Assuming a minimum acceptable SPI of 0.65, only B, C, D, and E are solutions. Adding a maximum cost constrain of 1.0 reduces the solution set to B and C. Under these constraints B is the best choice. In this example the technologies tend to fall into two time epochs, T1 and T2. If a minimum acceptable SPI of 0.9 is desired and a capability is needed before T2, we might consider implementing B in time epoch T1 and D in time epoch T2, assuming cost constraints can be relaxed. Otherwise, none of the technologies offer a viable solution within the constraints.

Conclusions and Recommendations
A methodology using a System Performance Index for assessing and ranking BMD technologies has been outlined. This

methodology addresses the questions of system performance, cost, and availability for insertion. It is objective, based on the physics of the problem, and avoids the problems encountered with subjective weighting schemes. The methodology completely characterizes the technology with respect to a baseline using the SPI, R, C, and ROI measures and utilizes the TRL and TOI measures to quantify readiness. It can quantify the effects of multiple technologies, as well as small effects by a technology in multiple areas. Further, it provides a framework for systematic tradeoffs between performance, cost, and time of insertion.

The SPI and R can be calculated using proven and accepted tools, which are available today, with only minor additions. It is recommended that a standard set of tools be adapted for all BMD technology assessment and prioritization work.

The methodology requires a cost model to compute total ownership cost. The system LCC models, element cost models, or other accepted cost models could be used to support this methodology. It is recommended that a standard cost model be adopted to support this methodology to ensure consistency of results.

The NASA methodology for determining the technology readiness level, which has been adopted by the Army, provides a useful measure of where the technology is in its developmental cycle, but is not sufficient. The TOI, which answers the important question of when the technology will be ready for insertion, is today a manual process that relies entirely on the technologist's input. It is recommended that a model be developed and validated to predict

when the technology will be available for insertion.

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List of Acronyms

ACEIT – Automated Cost Estimating Integrated Tools

BMD – Ballistic Missile Defense

BMDSAS – Ballistic Missile Defense System Architecture Studies

C – Cost Matrix

COCOMO – Constructive Cost Model

CPP – Critical Performance Parameters

DOD – Department Of Defense

GAO – Government Accounting Office

GBI – Ground Based Interceptor

JCTI – Joint Committee for Technology Integration

LCC – Lifecycle Cost

MEADS - Medium Extended Air Defense System

NASA – National Aeronautics and Space Administration

NMD – National Missile Defense

O&S – Operation and Support

P_S – Probability of Survival

P_{ZL} – Probability of Zero Leakage

QDA – Quick Defended Area

R – Resource Matrix

RDT&E – Research, Development, Test and Evaluation

REVIC – Revised Intermediate COCOMO

ROI – Return On Investment

SDI – Strategic Defense Initiative

SPI – System Performance Index

T - Technology

THAAD – Theater High Altitude Area Defense

TOI – Time Of Insertion

TRL – Technology Readiness Level

USASMDC – United States Army Space and Missile Defense Command

V – Value Matrix